AFRL-VA-WP-TP-2003-328

THE EVOLUTION, REVOLUTION, AND CHALLENGES OF HANDLING QUALITIES

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SEPTEMBER 2003

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
September 2003	Conference Paper Preprint	

4. TITLE AND SUBTITLE
THE EVOLUTION, REVOLUTION, AND CHALLENGES OF HANDLING QUALITIES

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
N/A

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

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8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-VA-WP-TP-2003-328

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Vehicles Directorate
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10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/VACA

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-VA-WP-TP-2003-328

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
To be presented at the AIAA Atmospheric Flight Mechanics Conference, Austin, TX, August 11, 2003.

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. David Doman
Unclassified	Unclassified	Unclassified	SAR	32	**19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-8451

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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Abstract

The need for good aircraft handling qualities has been apparent since the days of the Wright Flyer. In the past decade, there has been a perception that this need has lessened as advanced concepts have evolved, in parallel with acquisition reform. The former has led those who are unfamiliar with the field of handling qualities to conclude that quantitative requirements are not necessary, as the latter has resulted in the elimination of the military specifications for handling qualities. This paper reviews the evolution of handling qualities and their specifications. It presents some ongoing challenges in the field to illustrate that handling qualities are still a critical issue for future aircraft.

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Introduction

The past twenty-five years have seen both evolutionary and revolutionary changes in handling qualities and in the ways that they are specified. In the late 1970s and early 1980s the hot topic was whether to free El alpha (L_α). In the 1990s it became pilot-induced oscillations (PIOs), and later the possible elimination of specifications altogether. Today, the most critical issues in handling qualities may be how to extend them to pilotless aircraft (Uninhabited Aerial Vehicles or UAVs) and how to prevent undesirable phenomena such as PIOs and structural interactions.

There is an impression among the engineering community that handling qualities are not an issue today. This impression is wrong.

This paper provides a summary of the evolution of handling qualities by focusing on their specification, and the revolution by focusing on the contents of those specifications. It is not intended to be a comprehensive historical treatise on handling qualities; for that, the reader is referred to articles by Phillips[1] and Ashkenas,[2] and a book by Abzug and Larrabee.[3] Instead, the goal of this paper is to convey the path that has been followed to get where we are in the specification of handling qualities for fixed-wing airplanes, helicopters, and vertical/short takeoff and landing (V/STOL)

aircraft, and to show the open areas that lie ahead, at least for the near future.

Flying Qualities? Or Handling Qualities?

Most military and civil specifications explicitly refer to "flying qualities," not handling qualities. (The former military specification for helicopters, MIL-H-8501A,[4] does both: it applies to "flying and ground handling qualities," hence separating "handling" to mean ground handling only.) Phillips[1] defines flying qualities as "the stability and control characteristics that have an important bearing on the safety of flight and on the pilots' impressions of the ease of flying an airplane in steady flight and in maneuvers." In this paper, we intend to include the basic stability and control (S&C) characteristics referred to by Phillips, but to cover a more broad interpretation consistent with that put forth by Cooper and Harper:[5] handling qualities are "more than just stability and control characteristics. Other factors that influence the handling qualities are the cockpit interface (e.g., displays, controls), the aircraft environment (e.g., weather conditions, visibility, turbulence) and stress..." Cooper and Harper define handling qualities to be "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." They also note that "The generally accepted meaning of 'Flying Qualities' is similar to this definition of 'Handling Qualities'..."

In this paper, reference will be made to handling qualities except when specific reference is made to flying qualities specifications. This distinction is not meant to infer any change in meaning, but rather is done to be consistent with the familiar titles of the specifications themselves (i.e., MIL-F-8785C[6] is perhaps the most widely known aircraft specification we will mention, but it is a "flying qualities spec," not a "handling qualities spec.")

A Timeline

Interest in aircraft handling qualities is not new. It certainly began long before the Wright Brothers' first powered flight in 1903. Though the term was not yet used, developers of gliders and unpowered aircraft in the centuries before the Wrights also had an interest in the subject.

For our purposes, however, the timeline may be started with the first flight of the Wright Brothers, since it spurred the most intense efforts to understand and quantify the stability, control, and dynamic responses of the flying machine.

A graphical timeline is shown in Figure 1. This timeline reflects the most significant achievements in handling qualities over the last century, marked by reference to the relevant specifications for those achievements. Selected significant firsts in aviation history are added for reference, beginning, of course, with Orville Wright's 1903 flight.

What might be interpreted as the first "handling qualities" requirement was released in January 1908. It was a one-page document outlining the performance requirements for an aircraft in a sole-source procurement to the Wright brothers.[7] Among the requirements was the single line: "It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time." Fortunately, there were no requirements on what was meant by an "intelligent" man or a "reasonable" time.

It may be argued that the first real specification for flying qualities was written by Robert Gilruth and published by the National Advisory Committee for Aeronautics (NACA) in 1943.[8] In the same year, the US Army Air Forces and US Navy issued documents (both originally carrying Confidential classifications, since they were issued during World War II) that specified "Stability and Control Requirements for Airplanes."[9] The military documents had requirements that were similar in form to those written by Gilruth. Requirements for longitudinal and lateral-directional short-period motions specified only a single limit on number of cycles to damp; rolling performance was specified in terms of the rolling parameter pb/2V. One difference between the sets of specifications is that the military documents included flight test procedures for compliance, while the Gilruth report discussed design considerations for each of the requirements.

In 1948, the classified military specifications were reissued in revised format without classification, and with the title "Specification for Flying Qualities of Piloted Airplanes."[10] They were still essentially S&C specifications. The first helicopter flying (and ground handling) qualities specification, MIL-H-8501, was released in 1952,[4] with relatively simple time-response requirements on stability and control power and damping requirements stated in terms of weight and inertia. A single tri-service specification for fixed-wing airplanes, MIL-F-8785, was issued in 1954,[11] with more elaborate requirements for control characteristics but still relatively simple limits on modal responses. Lateral-directional oscillatory mode requirements were more complex, with a damping parameter $1/C_{1/2}$ specified in terms of a rolling parameter $|\phi/v_e|$. For the first time, requirements for power- and boost-control systems were included.

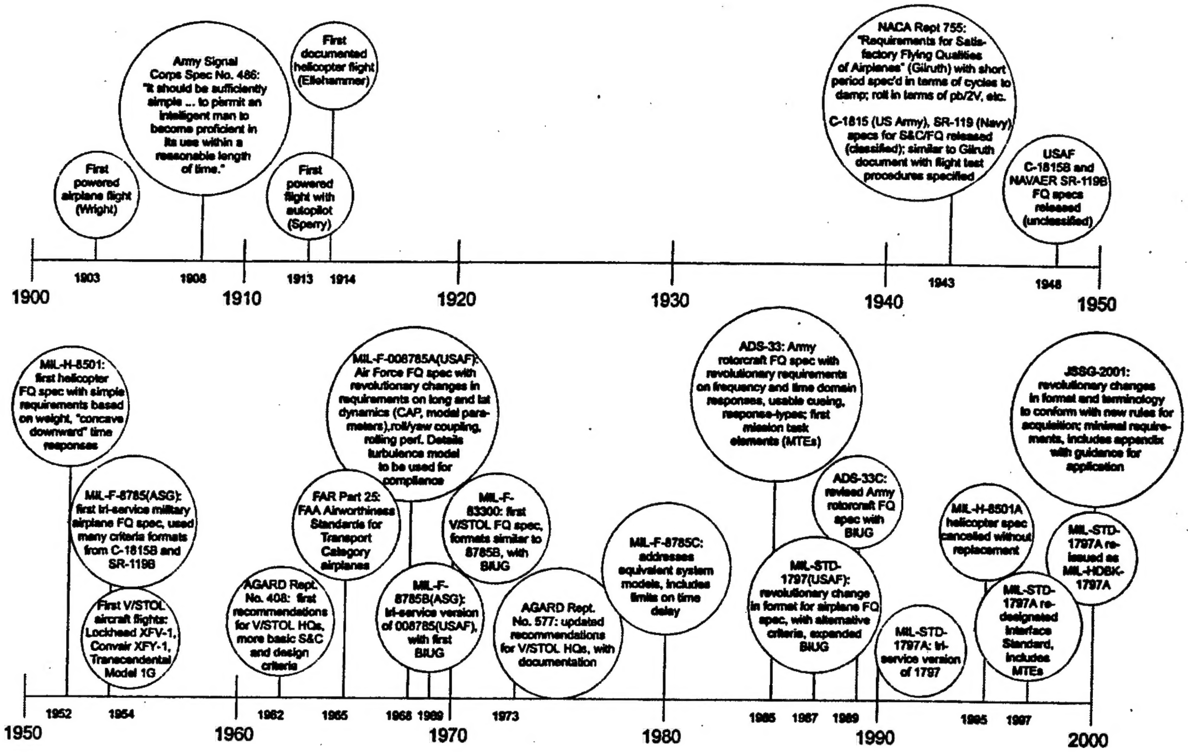

Figure 1. A timeline for handling qualities, including selected significant firsts in aviation history

Also in 1954, the first variable-configuration vertical/short takeoff and land (V/STOL) aircraft flew.[12] Eight years later, the NATO's Advisory Group for Aeronautical Research and Development (AGARD) issued a document with recommendations for V/STOL handling qualities.[13] Shortly thereafter the US Federal Aviation Administration issued its first airworthiness standards for civil aircraft, FAR Parts 23[14] and 25.[15]

Perhaps the most significant revolution in handling qualities took place in the late 1950s and early 1960s as concern for dynamic responses shifted from cycles and times to damp to modal parameters – short-period damping and frequency, phugoid damping, roll time constant, etc. In addition, the critical importance of turbulence on the specification of flying qualities requirements was recognized. An organization first affiliated with Cornell University in Buffalo, NY, Cornell Aeronautical Laboratory (CAL, later Calspan and now part of Veridian), was performing numerous flight research experiments with variable-stability aircraft. This work, along with Bihrle's efforts to describe the pilot's control of flight path in terms of a "Control Anticipation Parameter" (CAP),[16] led to the creation of a revolutionary new military specification, first issued by the Air Force in 1968 as MIL-F-008785A(USAF)[17] and the next year as the tri-service document MIL-F-8785B(ASG).[18] Complete documentation of turbulence models to be used for compliance was included as a part of the specification itself.

A breakthrough that accompanied the publication of MIL-F-8785B(ASG) was the issuance of a "Background Information and User Guide" (BIUG)[19] authored by CAL and Air Force engineers and containing a wealth of supporting information and application guidance. Such BIUGs have now become almost essential as the specifications have continued to increase in sophistication. Unfortunately, the original BIUG was released with export controls in place and hence was not easily obtained by non-US entities.

All fixed-wing military documents released since 1969 reflect the fundamental requirements stated in MIL-F-8785B(ASG), as do many of the requirements of the first V/STOL military specification, MIL-F-83300,[20]. issued in 1970 with its own BIUG.[21] The Air Force officially adopted MIL-F-83300 for all vertical-lift aircraft, including helicopters, though the Army and Navy continued to use MIL-H-8501A[4] until 1995.

A 1980 revision to the fixed-wing specification, MIL-F-8785C,[6] contained some apparently minor – but, in the ensuing years, controversial – revisions to address the "equivalent airplane." A BIUG for this specification discusses some of the issues faced in the revision.[22]

A second revolution in handling qualities occurred in the early 1980s as the US Army was formulating a replacement to the helicopter specification MIL-H-8501A. With the planned procurement of a new LHX helicopter (now the RAH-66 Comanche), the Army funded efforts to devise new criteria that reflected the extreme environments in which modern helicopters were required to operate. The culmination was an Aeronautical Design Standard, ADS-33,[23] that included frequency-domain requirements and the interactions of visual cueing and displays. This document included the first specific mission tasks (Mission Task Elements, MTEs) expected of the aircraft to demonstrate satisfactory handling qualities. For the first time, handling qualities requirements were written explicitly in terms of the Cooper-Harper Handling Qualities Rating scale. More is written about this specification later in this paper.

A revision to the Army's specification, ADS-33C,[24] was issued in 1989 along with its now-ubiquitous BIUG[25] (again carrying a limited distribution statement). The most recent version of ADS-33 was issued in 2000 as ADS-33E-PRF,[26] the added "PRF" indicating that the US Army has declared it to be a performance specification.

Reflecting changes in acquisition strategies, the fixed-wing specification underwent major changes in appearance in 1990, with the tri-service release of MIL-STD-1797A,[27] and again in 2000, with the Joint Services Specification Guide JSSG-2001.[28] Both documents move away from the explicit requirements of their predecessors, instead offering alternatives with considerable discussion to help the user select the most appropriate criteria. These documents thus incorporate more than just the criteria contained in MIL-F-8785C, as they include the works of many other researchers from the 1970s and 1980s. More discussion of the fixed-wing specifications follows in the next section of this paper.

The Evolution: Airplane Handling Qualities Specifications and Their Requirements

Dynamic Criteria and Equivalent Systems

The understanding of airplane dynamics developed along with the development of the airplane itself. This led to the dominant modes of response, i.e., the short period, phugoid, roll, Dutch roll and spiral modes, which explained conventional airplane responses to acceptable accuracy initially. Military flying quality requirements were specified in terms of acceptable values for parameters of these dominant modes. The introduction of stability and control augmentation began to change this situation, allowing for additional and/or higher-order modes plus arbitrary shaping of responses. Application of the classical mode parameters became more and more questionable. This ambiguity led to the "equivalent system concept."[29] This approach was included in the formulation of MIL-F-8785C published in 1980.

The equivalent system approach meant that the actual aircraft dynamics had to satisfy flying quality requirements in terms of "equivalent classical systems which have responses most closely matching those of the actual aircraft." The military specification requirements then apply to those equivalent parameters rather than to any mode of the actual response. As explained by Moorhouse & Woodcock:[22] "In order to demonstrate compliance with the modal requirements of MIL-F-8785C, equivalent systems must first be defined to approximate the actual airplane dynamics..." The equivalent system had to be calculated by a least-squares match to the actual/predicted dynamics over an appropriate frequency range, but there was no requirement on the "goodness" of the fit. That question was subjectively addressed by the authors' stated expectation that satisfactory flying qualities would be expected to result from a classical-type response that met the classical requirements. This preserved the existing database of the different Levels of the preceding version of the specification. There was also much discussion of this new method and a caution that "no method should be used blindly, without exercise of engineering judgment." One explicit requirement was that all nonlinearities had to be included in the response that was matched. This was supposed to tell designers that the specification was not just to be applied to linear analyses. At this time it had also become apparent that an undesirable trend introduced by more and more augmentation was increased phase lag in the responses to pilot commands. This was addressed by a new specification parameter, equivalent system time delay. In the terms of the frequency responses this was to be a term, $e^{-\tau_e s}$, added on to the classical formulations. The term, τ_e, was supposed to be "total effective time delay contributed by all sources including high-frequency flight control system modes (actuators, compensation, etc.), digital sampling and computation delays, etc., etc." A significant amount of data validated a degradation in pilot rating as this term increased, with the well-known (but often ignored) value of 100msec maximum equivalent system time delay for Level 1 flying qualities.

In summary, the equivalent system approach was supposed to represent the complete airplane dynamics and guide flight control designers to produce a system with good classical types of response modes that would be natural to a pilot. There are nuances that remained,

but it is our opinion that this approach is still the most valid one in general terms.

Alternative Design and Specification Criteria

Although the equivalent systems technique proved to be a reasonably successful approach to specifying dynamic response for highly augmented aircraft, it had at least one weakness. The LOES form used for the match was a conventional response form, and thus the criteria, as published in MIL-F-8785C, constrained the dynamic response to a "classical" response form (i.e., for longitudinal response, an alpha-command or a pitch-rate-command response type with no attitude-hold). This was somewhat of a weakness because, with the advent of fly-by-wire control systems and, shortly thereafter, digital flight control computers, flight control engineers now had an unprecedented capability to tailor the dynamic response to optimize handling qualities for individual flight tasks throughout the flight envelope. "Nuisance" modes such as the phugoid and Dutch roll could now be eliminated, but the equivalent system form in use in MIL-F-8785C assumed their presence. Of course, new lower-order equivalent system forms could have been identified for each response type (there were really only a handful that might plausibly prove useful), but no data existed to support criteria for such unconventional response types. Providing sufficient data for validated criteria for all of these additional response types would have been time consuming and costly; the very thing that the lower-order equivalent system approach had been created to avoid.

Consequently, research in the 1970s turned to devising new criteria that could be used to specify dynamic response characteristics regardless of response type. Such criteria could take advantage of the extensive conventional flying qualities data from past research without constraining the flight control engineer to a "classical" form. For obvious reasons, most of these criteria would focus on the shape of the aircraft's frequency response.

At the beginning of the decade, new data was becoming available for aircraft with higher order control systems. One of the earliest, and most extensively used databases from this time period is the Neal-Smith database. This database was created using the NT-33 variable-stability aircraft, and Neal and Smith derived alternative criteria from this data based on wrapping a closed-loop pilot model around a model of the vehicle's longitudinal dynamics and control system. Pitch tracking performance of the pilot-vehicle system was specified, and the criteria were based on the compensation the pilot model was forced to adopt to meet the performance specification and on the closed-loop resonance of the pilot-vehicle system. Technically, these criteria still steered the control system engineer into a pitch-rate-command response form because the performance criteria assumed a pitch tracking task (which this form is ideal for given the assumed pilot model) and the database consisted entirely of conventional (though higher-order) response types. Nevertheless, the criteria must be mentioned here because they were one of the most widely accepted alternative criteria and the database from which they were derived was also the foundation for many of the other alternative criteria addressed below.

Another approach, developed in the mid- to late-70s, became known as the Smith-Geddes criteria. This approach, as originally conceived, included a mix of time-response and frequency-response criteria. The criteria of the time response part specified the time to peak pitch rate following a step pitch control input. As with most other time response criteria, this criterion favored pitch-rate-command response types because the data upon which the criterion boundaries were based was exclusively conventional response types.

The frequency domain part of the Smith-Geddes criteria consisted of three components. The first component was the average slope of the amplitude curve of pitch attitude frequency response to stick force. This average slope was obtained from a straight line approximation of the amplitude curve over a frequency range in the heart of the pilot's frequency range of interest. The second component was the phase angle of the pitch attitude response to stick force at a specific frequency. This frequency, known as the criterion frequency, was basically an approximation of the crossover frequency of the closed-loop pilot-vehicle system. The third component, known as the normal acceleration phase parameter, was computed from the phase angle of the normal acceleration response to stick force at the criterion frequency.

The time-domain part of the Smith-Geddes criteria has not been widely used. The frequency-domain elements have been widely used, but not necessarily accepted. The weakest part of the criteria seems to be the estimate of the corner frequency. The formula for this estimation was based on data from a fixed-base compensatory tracking experiment by McRuer and others in the mid-60s. The Smith-Geddes formula derived from this data has not proven to be a very accurate estimate of the crossover frequency in actual flight tests. However, some users have found the criteria to be effective when a more accurate estimate of the actual crossover frequency is used. Another weakness of the criteria is that the values for the criteria boundaries were based on the Neal-Smith database (fighter-like dynamics), but the criteria have been claimed to be valid for all classes

of aircraft. Consequently, when the Smith-Geddes criteria have been applied to larger aircraft, like the B-1, B-2, and C-17, the criteria were impossible to meet without alteration, though they did accurately reflect trends (i.e., improvement versus the criteria reflected improvement in aircraft handling).

Demonstrating Handling Qualities with the Pilot in the Loop

The Need for Demonstration Maneuvers

It is recognized by the authors of this paper and others in the handling qualities community that the specification of handling qualities in a single reference will never be complete. Advances in flight control systems, cockpit controllers, and aircraft effectors may always outpace the advances in handling qualities criteria. In addition, some deficiencies in handling qualities, such as pilot-induced oscillations (PIOs), may not always be exposed by these criteria. Furthermore most requirements are intended to be applied to one axis at a time, so there are no catch-all criteria that insure that multiple-axis operations will be acceptable. Thus, the final verdict on the suitability of a prototype aircraft design must come from piloted evaluations.

Until recently, there has been no uniform set of published fixed wing aircraft maneuvers to guide the evaluations. In the past, flight testing for "handling qualities" has consisted mostly of open-loop steps and doublets to verify dynamic characteristics against quantitative requirements taken from the military specifications. Typically, if closed-loop flight testing, such as Handling Qualities During Tracking (HQDT), is conducted, it is introduced to the development process only after the prototype is flying.

Maneuver Set Requirements

The only way to insure that pilot-in-the-loop testing is (a) performed, (b) performed to a consistent standard of judgment, and (c) required from the beginning, is to specify the maneuvers and their definitions prior to procurement. Any such maneuver set should meet a number of specific requirements that include the following:

- Applicability to specific mission task elements. Using the mission-oriented approach proposed by Mitchell *et al.*,[30] mission task elements (MTEs) that directly reflect the operational missions of current and future aircraft were defined. A proposed categorization of these mission elements, divided on the basis of requirements for precision and aggressiveness, was then developed. The ultimate goal is to define a maneuver corresponding to every mission task element.
- Ease of flight testing. Some maneuvers will be inherently hazardous for a new prototype design; for example, aerial refueling or precision landings will always be approached in a build-up program, rather than attempting such a maneuver early in a flight test program. Others may be impractical from either a logistics or schedule standpoint. Most maneuvers that fail this requirement fall more into the category of aircraft performance or mission suitability tasks, rather than handling qualities evaluation tasks.
- Ability to define the task and constrain performance. This is simply an adjunct of the preceding objective: maneuvers that are easily flight tested are those for which the task scenario is repeatable and handling qualities performance limits are definable.
- Coverage of all levels of maneuver amplitude. Most of the handling qualities requirements and tasks in use today emphasize small-amplitude control. This certainly makes sense, since problems endemic to modern aircraft will typically be exposed by such tasks. There is, however, a need to assure that the moderate- and large-amplitude characteristics of current and future aircraft are also acceptable. While there are some such requirements (dealing with, for example, control force per g, time to roll through a specified bank angle, etc.), there is a shortage of tasks that emphasize maneuvering at elevated load factors or that involve g capture or large rolling maneuvers. These types of tasks are especially challenging in defining performance criteria that are both meaningful and measurable.
- Adaptability to all aircraft classes, response-types, and levels of visual cues. A common criticism of the current requirements is that they have a "fighter bias," since almost all of the quantitative criteria were developed for, and apply primarily to, high performance aircraft. There have been steps taken to remedy this situation, including development of pitch attitude and flightpath response requirements for transports.[30] The demonstration maneuvers must also reflect all classes of aircraft. In some cases, of course, the specific mission task element relates to a

specific class of aircraft; for example, tracking a combat maneuvering target would not be expected to apply to transports. On the other hand, some tasks may apply to all classes, including not only landing, but also in-flight refueling as the receiver.

An Initial Catalog of Fixed-Wing Maneuvers

In June 1995, the Military Standard for Flying Qualities of Piloted Aircraft became a Department of Defense Interface Standard.[27] This modification to the standard included several recommended maneuvers for the evaluation of handling qualities. These thirteen maneuvers represent the first step toward an integrated document, with both quantitative and qualitative requirements, for fixed wing aircraft. The 13 maneuvers in the Notice of Change to MIL-STD-1797A were as follows:

- Air-to-Air Gross Acquisition;
- Air-to-Ground Gross Acquisition;
- Air-to-Air Fine Tracking;
- Air-to-Ground Fine Tracking;
- Close Formation;
- Aerial Refueling: Boom Tracking;
- Aerial Refueling: Probe-and-Drogue;
- Offset Precision Landing: Approach;
- Offset Precision Landing: Touchdown (Conventional Aircraft);
- Offset Precision Landing: Touchdown (STOL Aircraft);
- Offset Precision Landing: Rollout and Takeoff Roll;
- Takeoff Rotation;.and
- Takeoff Climbout.

The next step in developing a more complete set of demonstration maneuvers was a USAF-sponsored Demo Maneuvers program[31] that resulted in a maneuver catalog.[32] The above maneuvers made up the core set of the demonstration maneuvers. Several of them have undergone modification or clarification, while others were used essentially intact. A number of the Standard Evaluation Maneuver Set or STEMS tasks that were developed by McDonnell Douglas for high-angle-of-attack flight evaluations[33] were also included in the final document following a flight test evaluation using the NASA F/A-18 High Alpha Research Vehicle.[34]

As part of the Demo Maneuvers program, consideration was given to a number of fundamental issues before revising existing maneuvers or defining new ones. The first issue was overshoot requirements. For the maneuvers included in the maneuver catalog,[31] initial overshoot of the target within a specified magnitude limit was permitted. Next, attempts were made to maintain operational relevance whenever possible. Some maneuvers, however, emphasized an isolated vehicle response, while others featured tightened performance requirements to better expose deficient handling qualities that may have otherwise been missed. The performance requirements were defined to facilitate use of the Cooper-Harper handling qualities ratings scale, but not to be rigid "pass/fail" criteria. Furthermore, the maneuvers that feature continuous closed-loop control were also used to assess pilot-induced oscillation (PIO) tendencies. Finally, the maneuver descriptions do not mandate flight condition or aircraft configuration. It is left to the end user to conduct evaluations with a particular maneuver at all relevant flight conditions and in all relevant aircraft configurations.

The maneuver catalog is designed to be a living document in that revisions and additions are anticipated and desired. For example, the recent work involving the assessment of the ground handling of a Navy aircraft produced a set of ground handling maneuvers.[35] These maneuvers would enhance the existing catalog by addressing an area that has been largely ignored. Other enhancements may include carrier operations for naval aircraft and V/STOL operations, especially as the JSF program moves forward.

The Revolution: The Rotary-Wing Specifications

The First Spec: MIL-H-8501

The helicopter handling qualities specification MIL-H-8501A[4] was a 1961 revision of a 1958 document. There was no related report to explain the basis or rationale for the various handling qualities criteria. The primary requirements consisted of limits on simple time domain parameters such as control stick force and position gradients with speed, frequency and damping of oscillatory modes, normal acceleration response to a step input, and angular displacements in response to control steps that are a function of the helicopter weight. Some distinction was made between day VFR and night IFR requirements, but flight in low visibility conditions was not considered.

Several studies were performed to assess MIL-H-8501A usefulness. For example, in 1967 Ashkenas and Walton[36] compared the various requirements with analytically derived criteria and any available handling qualities data. Even with linear analysis and sparse data, the study did identify many inconsistencies and shortcomings in the requirements. The requirements did nothing to address the highly coupled mode characteristics that helicopters exhibit, let alone the significant cross couplings and nonlinearities. With the

many years to overcome most of these limitations. Fortunately the Canadian National Research Council Flight Research Laboratory operated an in-flight simulator in the form of a variable stability Bell 205,[43] and generously collaborated on many investigations such as the multi-axis side stick controller study.[44] The combination of ground based survey investigations and in-flight validation eventually generated a significant body of data on which quite substantial criteria could be based. In later years the German Aerospace Laboratories DLR added to the team with their variable stability BO 105. To this date the US does not have an equivalent in-flight simulation capability, and funding to even keep the NASA simulators up to date is in question.

Significant effort to develop criteria and a new specification started in 1982. A version hurriedly prepared so as to be available for a pending Army program to develop a new light scout-attack helicopter (LHX) was adopted by the US Army as Aeronautical Design Standard –33 in 1985. Revisions to refine and expand the coverage continued into 2000 with the version ADS-33E-PRF;[26] a draft test guide for the specification was produced in 2002.[45] Time lines of various versions and activities is shown in Figure 2.

ADS-33 not only produced criteria based on a substantial research data base, but also introduced several concepts that have revolutionized the topic of handling qualities specification, design, test and evaluation. Innovations include:

1. An empirical method for determining the quality of visual cues actually available in the design when in the operational environment (Visual Cue Rating VCR and Usable Cue Environment UCE).

2. A menu of tasks (Mission Task Elements MTE) that are appropriate for each helicopter category (scout, attack, utility, cargo, and configurations with external sling loads).

3. A description of each MTE in sufficient detail for it to be used by test pilots in formal evaluations. This includes the evaluation task objectives, the required maneuver, an appropriate test course or ground references, and desired and adequate performance standards.

4. Stability or stabilization requirements that are graded according to the visual environment that will be encountered (Usable Cue Environment UCE).

5. Control and maneuvering requirements that depend on the applicable MTE.

6. New parameters for specifying required short term response to control (bandwidth).

7. New parameters for specifying required moderate and large amplitude control power (attitude quickness).

8. New parameters for specifying allowable pitch-roll cross coupling during aggressive maneuvers.

Descriptions of each of these topics are contained in ADS-33E-PRF.[26] Background data and rationale is given in the BIUG.[25] Clearly space in this paper will not accommodate even a summary of these topics, so interested readers should consult the referenced documents.

The overall specification format satisfies the 1994 Department of Defense edict that specifications must be "in the form of performance standards and must be tailorable for a specific end item."[46] Another innovation of ADS-33E-PRF was the way in which tailoring was incorporated into the overall structure. This tailoring process and an illustration of how it all fits together in a system development is described below.

Structure of ADS-33E-PRF

The structure of ADS-33E-PRF is indicated in the schematic, Figure 3. Tailoring the requirements for application to a specific rotorcraft is performed as follows. The operational missions should have been defined by the user and included in the system specification for the rotorcraft. Knowledge of these operational missions is used as a basis for selecting the applicable Mission Task Elements (MTE) from the provided candidates. The system specification should also have defined the desired operational environment; specifically, the visibility and light level, and performance capabilities of any pilot's vision aids. Also defined by the user should be the desired extent of IMC capability, slope landing capability, and the degree of divided attention.

Once the specific helicopter's tailoring items have been determined, selection of the applicable requirements and standards are explicitly prescribed. Procedures are given for determining the Usable Cue Environment (UCE) using the planned vision aids. Related to the UCE are the required Response-Types that define the amount of stabilization required. ADS-33E-PRF makes a direct connection between the selected MTEs and the required Agility. The required Agility and required Response Types together define which boundaries of the handling qualities design criteria apply, and which performance standards must be met, thus completing the tailoring.

The next step in using ADS-33E-PRF is to determine how well the rotorcraft design meets the design criteria throughout the Operational and Service Flight Envelopes (OFE and SFE).

development of MIL-8785B[18] in 1969, it became obvious that MIL-H-8501A also lacked many aspects of basic structure such as systematic treatment of levels of flying qualities, flight envelopes and reliability.

Despite recognized shortcomings, through the 1970s and 1980s the US Army and Navy continued to base its handling qualities requirements on MIL-H-8501A. For example, the handling qualities portions of the Prime Item Development Specifications for the UH-60[37] and AH-64[38] were essentially MIL-H-8501A. Similarly, the Navy based the handling qualities requirements for the SH-2, SH-60 and CH-53 procurements on MIL-H-8501A.

In a 1980 AIAA paper Key performed a review of the MIL-H-8501A shortcomings that had manifested themselves during the UH-60 and AH-64 developments,[39] and in 1982 Goldstein performed a similar review for the SH-60B and CH-53D Navy helicopters.[40] Both papers showed instances where the requirements were met but the helicopter was deficient, or failed and was acceptable.

Several attempts were made to update MIL-H-8501A. A notable example resulted in a draft by Pacer Systems in 1972. It contained several new ideas and suggested improvements, but like other attempts was foiled by a lack of systemic data on which to base criteria. A final document was never published.

V/STOL requirements: MIL-F-83300

Although there was a scarcity of handling qualities data for helicopters, by the late 1960s much work had been performed to understand the handling qualities of a hovering vehicle. Specifically vehicles with modest aerodynamic effects and relatively linear, uncoupled characteristics such as seemed to characterize emerging V/STOL aircraft. The USAF sponsored work to develop a specification for V/STOL aircraft and to include helicopters as far as possible. The result was published as MIL-F-83300[20] in 1970, and a related Background Information and User Guide (BIUG) was published in 1971.[21]

MIL-F-83300 followed the fixed wing aircraft specification MIL-F-8785B very closely in format, structure, and in the parameters used for many of the requirements. It explicitly addressed hover and low speed flight up to 35 kt and a forward flight or transition regime between 35 kt and V_{con}. At V_{con} the requirements were to blend into those of MIL-F-8785B.

This specification was adopted by the USAF for helicopters (though none were ever procured to this standard) as well as V/STOL aircraft. Neither the US Army nor the Navy adopted MIL-H-83300 for helicopters, instead, as noted above, they continued to use MIL-H-8501A. A 1972 AHS paper by Green[41] provided a long list of reasons that MIL-H-83300 was not acceptable for helicopters and that recommendation probably had something to do with the decision not to adopt it. In hindsight the author of this section, who was also a primary author of MIL-H-83300 and ADS-33, believes this was a wise decision. Not only were the helicopter idiosyncrasies of strong inter-axis couplings and significant nonlinearities, not adequately addressed, but all the stability and control data available at that time had been generated using typical V/STOL flight tasks, that is, sedate hovering and low speed maneuvering, or approach and landing. Such tasks were hardly representative of the Navy's ship landing or Army's nap-of-the-earth flying, especially in poor visibility. As Cooper and Harper state in their classic report,[5] "handling qualities are those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks require in support of an aircraft role." Hence, data was needed that related to the appropriate task and level of precision.

In the early 1980s the Navy sponsored some work to revise MIL-H-83300. One result was a report by Hoh and Mitchell[42] published in 1986. The primary revisions proposed were to replace the time response metrics for dynamic response with a frequency response measure (bandwidth) that had been developed to handle V/STOL aircraft with thrust vectoring capability. The Hoh-Mitchell recommendations were never incorporated into a revision of MIL-H-83300. The Navy adopted MIL-H-83300 for V/STOL aircraft and has been using it to guide development of the V-22 tilt rotor.

Current spec: ADS-33

By the mid 1970s concerned specialists knew that a new helicopter handling qualities specification was needed, but also recognized that the necessary data base did not exist. A major thrust to develop such a data base was eventually undertaken by the US Army Aeroflightdynamics Directorate with the help of NASA Ames Research Center. The primary tools for handling qualities research are ground based and in-flight simulators. NASA operated some of the most advanced ground based simulators but initially they had significant limitations for helicopters performing tasks representative of Army missions. The most advanced computers lacked the capacity to represent a realistic helicopter model in real-time. Visual systems could only provide a low detail, low resolution, narrow field of view image of the out-the-window scene, not very representative of flying down amongst the trees. It took

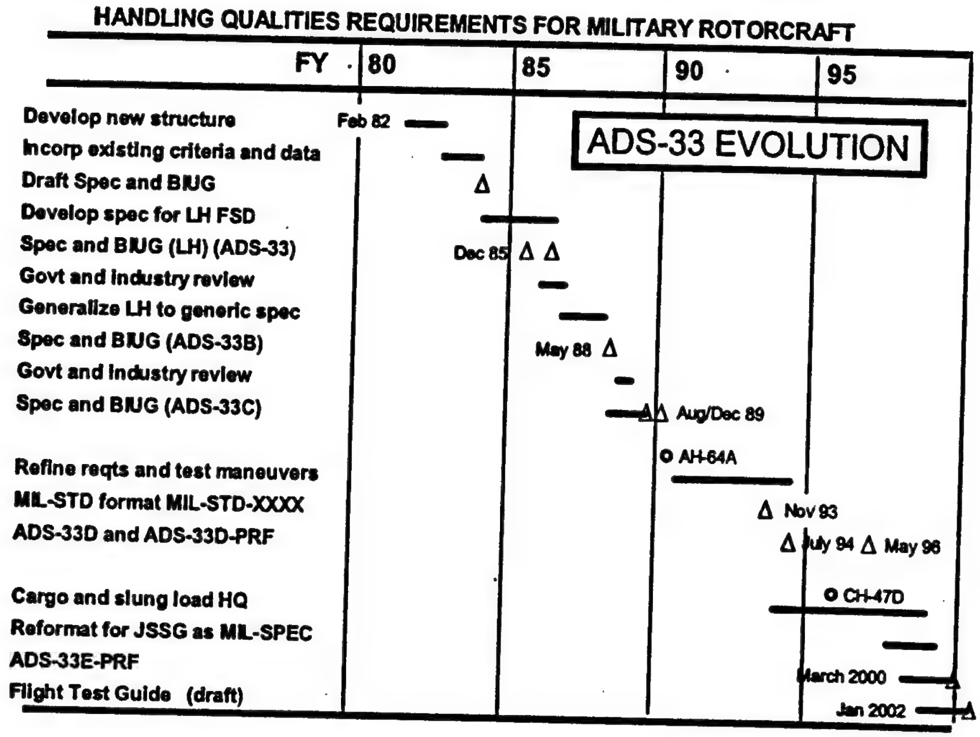

Figure 2. Timeline for the development of the rotorcraft handling qualities specification ADS-33

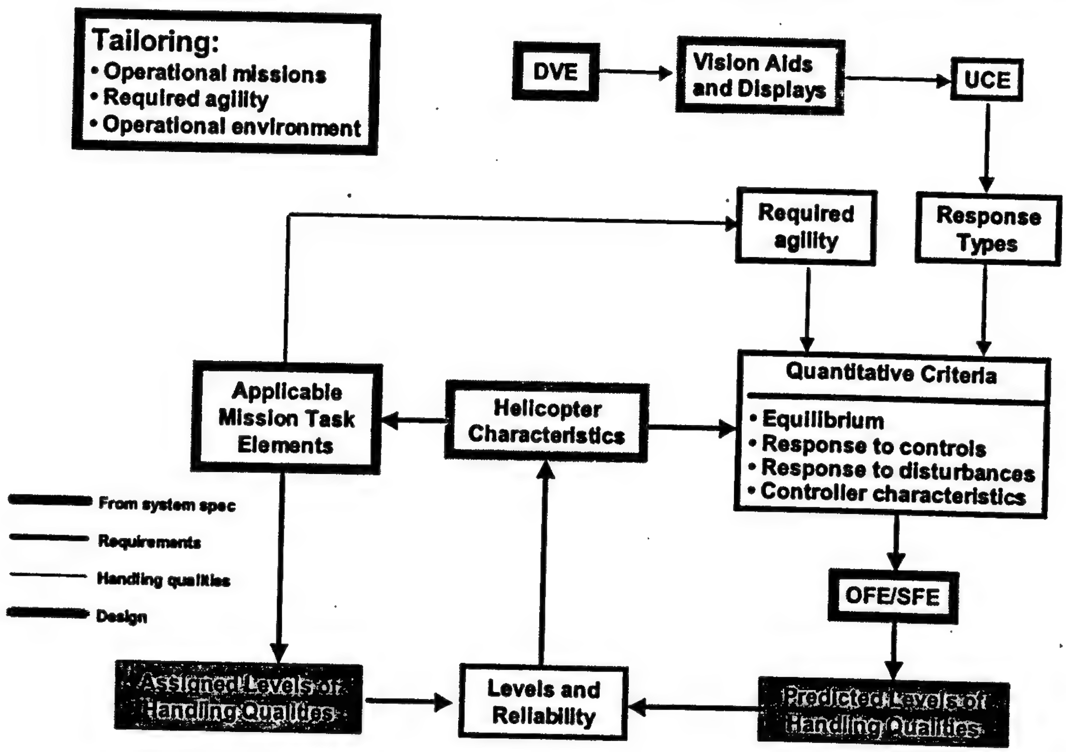

Figure 3. Structure of ADS-33E-PRF

How well the helicopter design meets the quantitative criteria may be determined analytically once the basic aerodynamic and flight control characteristics have been estimated. Together they provide a Predicted Level of handling qualities. Compliance with ADS-33 may therefore be evaluated early in the design process.

Once the design process has evolved to piloted simulation or flight, a sample of test pilots can fly the applicable MTEs and provide evaluation comments and handling qualities ratings. The results of these evaluations provide an Assigned Level of handling qualities.

By the time the rotorcraft is ready for System Verification Review (SVR), the developer should have made analytical and simulation assessments, backed up with flight data. OFE and SFE boundaries should be defined and correlated with the structural and aerodynamic limits. Margins between the OFE and the SFE limits will have been assessed, and appropriate cautions and warnings developed. A Failure Modes and Effects Analysis (FMEA) will have been accomplished and the handling qualities associated with the identified failed states will have been assessed according to the reliability requirements.

ADS-33 was applied to the Army's Light Helicopter (LHX) design. It provided a valuable basis for handling qualities assessment of the competing designs. During detailed design and development of the winning design, the RAH-66 Comanche, handling qualities specialists found it gave them a level of credibility when making design trade-offs that would previously have gone unheeded.

The Challenges

Pilot Modeling for Handling Qualities Applications

Origin of Control Theoretic Pilot Modeling

Numerous mathematical models of human operator behavior have been developed over the past 55 years, starting with the early work of Tustin.[47] Most pilot models used in flying qualities analysis today have been developed to model a pilot engaged in a compensatory tracking task. A compensatory tracking task is one in which the pilot is provided with a display of some tracking error that is to be regulated by the pilot through appropriate stick inputs. Most pilot models are based upon the idea that a pilot's behavior is similar to that of a well-tuned feedback control system, subject to the constraints of the human operator. These constraints account for a pilot's finite reaction time, limitations on limb-manipulator bandwidth and a remnant that includes the effects of divided attention, observation noise and control input errors. Both classical and optimal control theoretic pilot models have evolved over the years.

Classical Pilot Models and HQ Prediction

A number of flying qualities prediction techniques that are based on pilot models have been proposed over the past three decades.[48,49,50,51,52] A version of the Neal-Smith criteria,[48] developed in 1970, was included in MILSTD 1797A.[27] The Neal-Smith criteria can provide estimates of pitch-axis flying qualities using results based on an analysis of the closed loop pilot-vehicle system shown in Figure 4.

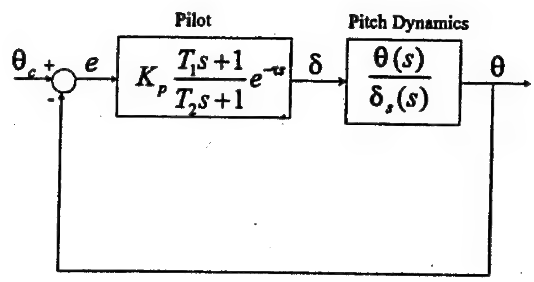

Figure 4. Closed-loop pilot-vehicle system

Flying qualities Levels are associated with regions in the two-dimensional plane, shown in Figure 5. Flying qualities estimates are functions of closed-loop resonant peak ($|\theta(j\omega)/\theta_c(j\omega)|_{MAX}$ dB) and the pilot model phase angle, exclusive of time delay, evaluated at a frequency representative of the mission task $\angle Y_p(j\omega_{BW})$. The closed-loop resonant peak is used as a frequency-domain measure of performance, while the pilot-model phase compensation is related to workload. It is well known that a human operator's perception of workload is influenced by the amount of phase compensation required to attain acceptable levels of performance.[53] The boundaries on Figure 5 were established by correlating Cooper-Harper ratings recorded from flight experiments with closed-loop resonance and pilot phase compensation parameters. These parameters are generated using a pilot model that is tuned using a specific set of rules[48] devised by Neal and Smith. The flight-test data used to create the Neal-Smith criteria was gathered from a series of in-flight simulations that used the USAF/Calspan NT-33A vehicle to systematically vary the pitch dynamics of the vehicle for the purpose of gathering Cooper-Harper ratings for a wide range of aircraft dynamics.

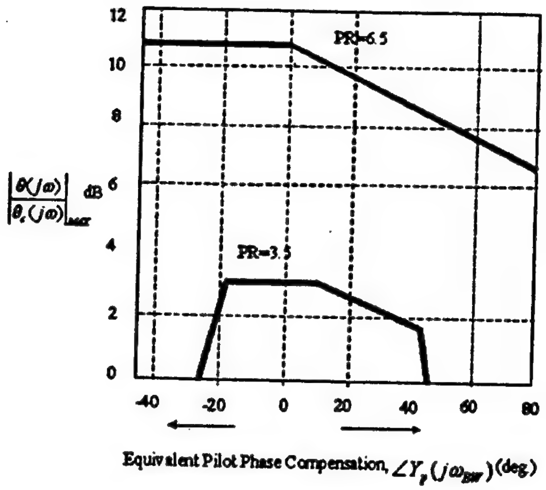

Figure 5. Neal-Smith criteria

HQ Prediction via Optimal Control Pilot Models

The fidelity of the Neal-Smith pilot model is limited because the structure of the model is constrained to that of a gain, a lead-lag filter, and time delay. While such a model structure can provide good matches to experimentally obtained data in the region of the open-loop pilot-vehicle gain crossover frequency, it fails to capture the characteristic low-frequency phase droop and higher frequency resonant peaks or shelves that are commonly observed in experimental data.[54,55] McRuer, *et al.*[54] demonstrate that a 5th order pilot model with time delay can provide an excellent match to describing function data for a single-axis compensatory tracking task. Higher order optimal control models (OCMs) are capable of capturing the salient features of experimental frequency response data over a wide frequency range.

The original OCM[55] and its many variants[50,51,56,57,58] assume that the pilot behaves optimally subject to human limitations. The pilot models are computed using results from Linear Quadratic Gaussian (LQG) control theory. Recent research[57] using a Fixed-Order Modified Optimal Control Model (FOMOCM) has concluded that a 5th order pilot model structure with time delay is the minimum structure that can accurately characterize a pilot's response over a wide frequency range. This research also indicates that frequency-weighted mean-squared tracking error must replace the traditional mean-squared tracking error in the OCM performance index to capture the low-frequency phase droop phenomenon that is frequently observed in experimental data. The frequency weighting reflects the fact that a pilot is less tolerant of long-term tracking errors than short-term errors.

There is also a body of work in the area that has concentrated on using high-fidelity optimal control pilot models to predict handling qualities ratings.[49,51,59] Bacon and Schmidt[49] developed a method of predicting flying qualities Levels based on closed-loop resonance and pilot phase compensation parameters generated by a high fidelity OCM. In Russia, Efremov *et al.*[50,51] have used a similar OCM-based approach to develop the Moscow Aviation Institute (MAI) criteria. The MAI criteria also use the familiar closed-loop resonant peak for a performance metric and a specially defined pilot phase compensation parameter as a workload metric. The pilot phase compensation is obtained by determining the maximum and minimum phase compensation generated by the pilot model. The MAI definition of phase compensation is based upon the notion of an optimum controlled element that is a function of the task (i.e., input spectrum) and operator time delay. For a given task and operator time delay, there exists a controlled element that requires only gain compensation by the pilot to achieve minimum RMS tracking error. Determination of the optimum controlled element is based upon a Wiener Approach.[50,51] Once the optimum controlled element is determined, an OCM analysis is performed. The OCM phase for the optimum controlled element is used as a standard of comparison for all other OCMs for different controlled elements. That is, the maximum and minimum phase compensation is defined as the maximum or minimum difference between the OCM phase for a given controlled element and the OCM phase for the optimum controlled element. MAI has shown that the OCM can provide accurate frequency response descriptions of experimental data and that the OCM-based metrics correlate to handling qualities ratings.

In any case, OCM models have much higher fidelity than the simple Neal-Smith pilot model and it has been shown that there exists a strong correlation between the performance and workload parameters generated by these sophisticated models and Cooper-Harper Ratings.

Other Uses for Pilot Models

One advantage that OCM methods have over classical methods is that they provide a systematic way to model human operators engaged in multi-axis tracking tasks. This multi-axis modeling capability is inherent in the LQG formulation and can be combined with divided-attention models to predict human operator response in cases where the pilot must maintain precise control of more than one axis, e.g., simultaneous pitch and roll tracking.

Control synthesis algorithms have been proposed that make use of optimal pilot models to optimize aircraft handling qualities.[60,61,62] These techniques make use of

empirically derived relationships between observed Cooper-Harper Ratings and a quadratic performance index that models the pilot's objectives. This performance index includes mean squared tracking error (tracking performance) and a weighted mean squared manipulator rate term (an indication of pilot compensation). These methods are based on the idea that an aircraft control system can be designed by adjusting control system design parameters so that the estimated Cooper Harper Rating is minimized. For a given control design, one can close the loop around the augmented aircraft with an optimal control pilot model and compute the cost function as well as a Cooper Harper Rating estimate. The control system parameters are then iteratively adjusted until a design results that has "optimal" flying qualities.

Optimal control models also have features that allow an analyst to model the interaction between the operator's time delay and phase compensation. The OCM can also account for different levels of physical conditioning or aggressiveness by varying the bandwidth of the pilot's response through selection of a neuromotor lag time constant. The neuromotor lag time constant effectively drives all of the state feedback gains in the OCM so that they are optimal subject to the band-limited nature of the pilot's response. The neuromotor lag; therefore, provides a means of characterizing "high gain" (high bandwidth) and "low gain" (low bandwidth) pilots. Low values of τ_n correspond to aggressive or high-bandwidth pilot behavior while higher values of τ_n reflect the behavior of low-bandwidth pilots. Pilot reaction time τ_p is another physiological parameter that varies among the population. Pilot time delay has a significant effect on performance and workload. Figure 6 shows OCM-based estimates of closed-loop resonance and pilot phase compensation for a range of neuromotor lag time constants and time delays for a fixed set of vehicle dynamics.

One can see that optimal-control-based models can provide a means to explore the sensitivity of pilot ratings to variations in physiological parameters. The use of performance and workload metrics from OCMs has also been proposed as a way of resolving conflicts resulting from inter/intra pilot Cooper-Harper rating variability.[59]

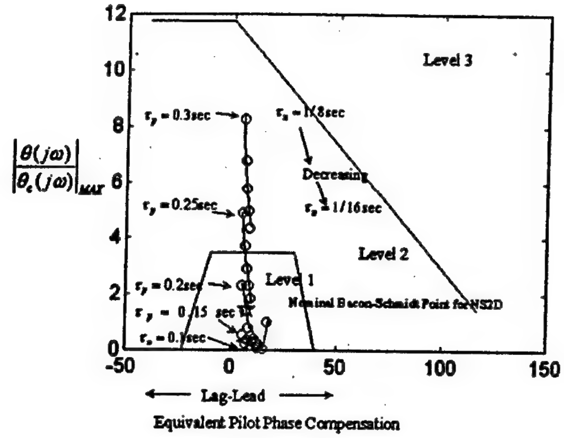

Figure 6. Sensitivity of estimated pilot ratings to variations in physiological parameters

Handling Qualities Requirements for Fixed-Winged V/STOLs

Modern aircraft often take advantages of the benefits of vectored thrust to enhance mission effectiveness. While this enhanced capability increases operational usefulness, it also presents certain design challenges to ensure that the aircraft can safely be piloted with enough precision to successfully accomplish all its primary mission objectives (night operations, over water, with turbulence, carrying an external load, with a fatigued pilot, etc.).

The current military specifications address the airplane mode characteristics (MIL-F-8785C) and V/STOL characteristics (MIL-F-83300) with minimal or no attention to the flying qualities requirements for transition or the advantages of operating entire mission scenarios at intermediate thrust vector settings. The modern rotorcraft military specification, ADS-33 is a significant improvement requiring quantitative data, qualitative data, and Mission Task Element (MTE) evaluations to demonstrate acceptable aircraft flying qualities. However, this specification does not currently address the capabilities or characteristics of variable thrust vector aircraft.

As such, there is no published set of comprehensive design requirements that specifically address variable thrust vector aircraft mission capabilities or the unique flying qualities characteristics of those aircraft. Individual programs have been left to their own devices to develop a list of flying qualities requirements, scavenging from old helicopter or airplane specification documents. What falls out is a long list of design "goals" from multiple military specification documents

that must be analyzed to show compliance. Since may of the design goals simply do not apply, numerous design "exceptions" will be required to address the thrust vector characteristics of the aircraft being designed. These exceptions add work to convince the user community that the aircraft provides adequate flying qualities to perform the mission without specifically meeting every line item in the helicopter or airplane specification documents.

V-22 Osprey Example

The V-22 Osprey Full Scale Development program began in the mid-1980s and was aimed at developing a multi-service, all-weather, special operations, amphibious aircraft with vertical/short field takeoff and landing capabilities not available without utilizing thrust vector, or tilt-rotor capability. The applicable military specifications at the time of contract release were MIL-F-83300 for S/VTOL aircraft and MIL-F-8785C for airplanes.

The V-22 contract specifies that the airplane specification be applied when the thrust vector setting is forward (nacelles at 0°) and the S/VTOL mode specification elsewhere (nacelles greater than 0°), as shown in Figure 7. To allow for unique flying qualities characteristics not encompassed by these specifications, however, the aircraft can be considered satisfactory in total if it meets the flying qualities requirements in Table 1. Level 1 flying qualities are defined in terms of Cooper-Harper pilot ratings between 1-3.5 and Level 2 flying qualities between 3.5-6.5. However, the program defined no specific mission relatable tasks. To fill this void, the V-22 program developed a set of mission task elements (MTE's) that are used to verify that the aircraft flying qualities are satisfactory in total, and more have been developed to augment the original list,[63,64] see Table 2.

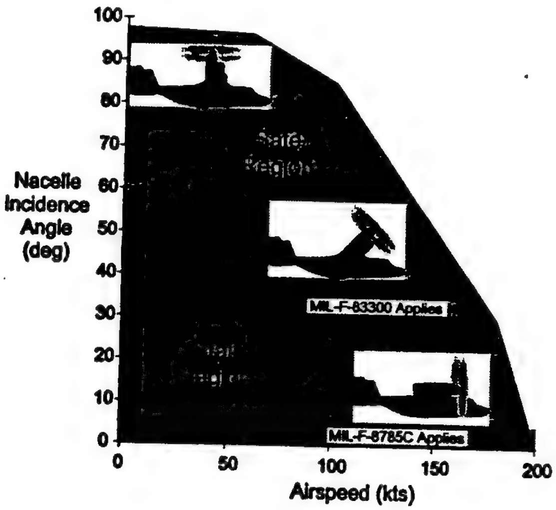

Figure 7. V-22 Military specification applicability

Table 1. V-22 flying qualities requirements

Within Operational Flight Envelope (OFE)	Within Service Flight Envelope (SFE)
Level 1	Level 2

The benefits of vectored thrust are numerous. The current military specifications, however, do not address these unique aircraft flying qualities characteristics in a single modern comprehensive document. The military community would benefit if a single military specification were developed to address the unique flying quality characteristics of vectored thrust aircraft with qualitative, quantitative, and MTE requirements, similar to ADS-33.

Table 2. V-22 Mission Task Elements

Helicopter Mode (Nacelles ≥75°)	Conversion Mode (Nacelles <75° & >0°)	Airplane Mode (0° Nacelles)	Variable Nacelles
1) Precision Hover 2) Lateral Reposition 3) Hover Pedal Turn 4) Vertical Reposition 5) Vertical Takeoff 6) Vertical Landing 7) Formation Flight	1) Short Takeoff 2) Altitude Change 3) Bank Angle Capture and Hold 4) Formation Flight	1) Altitude Change 2) Bank Angle Capture and Hold 3) Formation Flight 4) Aerial Refueling	1) Aborted Departure 2) Run-on Landing 3) Level Acceleration 4) Level Deceleration 5) Formation Flight

Pilot-Induced Oscillations

Pilot-induced oscillations (PIO, sometimes referred to as pilot-in-the-loop oscillations or pilot-involved oscillations) are a special subset of handling qualities that require special attention. Since "handling qualities" refers to those characteristics of the aircraft that govern its response under continual piloted control, we can consider handling qualities to be important throughout the aircraft's flight. By contrast, PIOs are "rare, unexpected, and unintended excursions in aircraft attitude and flight path caused by anomalous interactions between the aircraft and pilot."[65]

Hopefully, most aircraft go through their entire operational lifetimes without exhibiting a PIO. PIO must be addressed as a unique, but related, subset of handling qualities.

PIO in the Specifications

The military handling qualities specifications have addressed PIO, usually without identifying it as such. PIO can occur as a result of deficiencies in basic handling qualities characteristics, and since the specifications define what is desirable, meeting those specifications provides a first level of protection against the phenomenon. In 1995, the Smith-Geddes criteria were introduced in the fixed-wing standard MIL-STD-1797A[27] to specifically address PIO, though these criteria have not met universal acceptance.

For PIOs that result from linear aircraft dynamics, meeting the specifications should reduce the risk. Properly applied, the military specifications are also meant to account for the effects of common nonlinearities by requiring compliance for small and large control inputs. In reality, however, most severe PIOs that have occurred since at least the 1950s have involved some degree of nonlinear response that was neither expected nor accounted for by the military specifications.

Following some highly-publicized events with commercial aircraft such as the MD-11,[66] the US Federal Aviation Administration (FAA) became concerned about the occurrence of PIOs in civil transports. Several proposed flight test methods were drafted and distributed starting in the mid-1990s. The most recent version is included in the FAA's flight test certification guide.[67] In recent years, more PIOs have been reported in civil aircraft, and as of this writing a working group comprised of members of the FAA, Europe's Joint Aviation Authority (JAA), and industry is attempting to come to an agreement on a joint plan for testing for PIO. No formal action for developing a Federal Aviation Regulation dealing with PIO has been announced.

Handling Qualities and PIO

Most commonly, PIO occurs as a result of a nonlinear event, such as saturation of rate or position limits on a surface actuator, or from inappropriate flight control system (FCS) design, such as excessive filtering or lags. The nature of most PIOs is such that the airplane up until the onset of the oscillation is stable and seemingly well-behaved; encounter with some form of "trigger" leads the pilot into a situation where the closed-loop, pilot-vehicle system is neutrally damped or unstable (Figure 8).

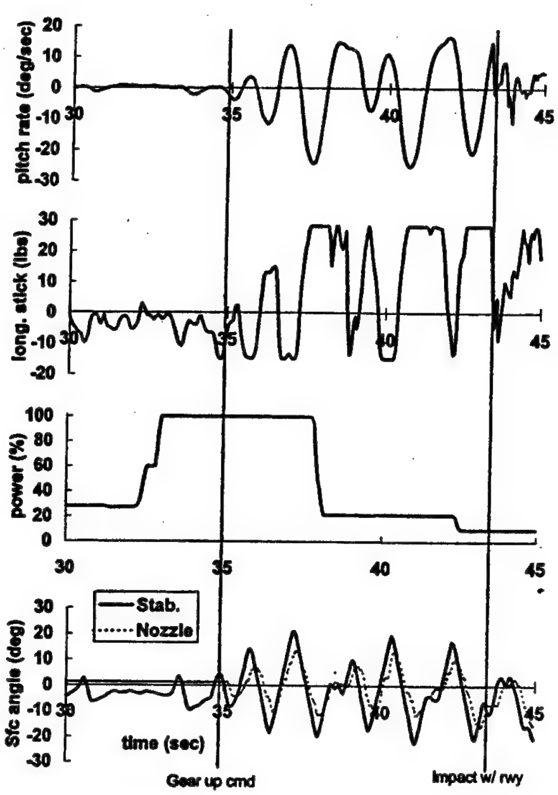

Figure 8. Time history of the YF-22 PIO

PIOs have occurred during the development process for almost every new airplane. Frequently the severity of the oscillations is sufficiently low that the PIO is detected and fixes applied to the airplane's FCS with little or no public acknowledgment of the event. Occasionally, however, either the severity, the frequency of occurrence, or the consequences of the PIO are such that it becomes headline news (for example, the YF-22 crash[68]).

Despite the ubiquitous nature of PIOs, it is also true that they always come as a surprise to the pilot and to the developers of the airplane. Typically, after a PIO has been encountered in flight, an intense research effort is

undertaken to determine the causes of the event and to understand why the tendency to PIO could have gone undiscovered for so long. In the case of the YF-22, among the findings of an accident review board were the need for application of analytical criteria throughout the development process, and the requirement for high-gain, closed-loop tracking tasks for evaluation of PIO susceptibility.[69]

In a report for the US Air Force, Mitchell and Hoh[70] outlined 10 steps for reducing the risk of PIO. The 10 steps are described below.

1. Be Prepared for PIO. – Experience has clearly demonstrated that it is almost impossible to avoid PIO in some form during the development process for any airplane. It is safe to say that at least one representative of just about every flying vehicle has experienced some form of PIO, from the 1903 Wright Flyer to the most modern transport airplane. Fortunately, the vast majority of these events are mild in nature and the cures are easily found. Given the wide variety of possible conditions, airplane designs, and triggers, it is practically impossible to make an airplane absolutely PIO-proof for its entire lifetime. If PIO is possible, the best defense against "surprise" encounters is to be prepared for the eventuality. This is especially important in a success-oriented development program, where the unexpected occurrence of PIO can threaten to cripple the entire project. Exploration for PIO should become a routine element in all phases of the development of a new aircraft.

2. Design for PIO Resistance. – This may seem like motherhood – after all, who is going to design for PIO susceptibility? – but the goal is to assure that the aerodynamics, flight control system, effector sizes and actuators, and cockpit control inceptors, are all specified with the prospects of PIO in mind.

3. Apply Valid Prediction Criteria Early in the Design Process. – As soon as the first set of aerodynamic derivatives is estimated, it should be possible to begin to apply criteria. Full application will require knowledge not only of the unaugmented airframe, but also of expected types and levels of augmentation, including, as early in the process as possible, reasonable models of surface actuators and cockpit inceptor dynamics.

Criteria recommended for application are based on pitch attitude and flight path Bandwidth and pitch rate overshoot, using the parameters defined in Figure 9 and Figure 10. It is preferable that the parameters always be measured with the dynamics of the cockpit control feel system included. Since this is sometimes impractical – such as during preliminary design, where the cockpit configuration has not been fully defined – the parameters may also be measured with the feel system excluded. Two sets of criteria plots are presented.

The core of the criteria is a crossplot of angular attitude Bandwidth frequency versus Phase Delay. Bandwidth measures the basic stability of the airplane and determines the frequency range over which piloted control is possible with a minimum of pilot equalization. Phase Delay measures the high-frequency phase loss if the pilot operates at high frequencies.

For the pitch requirements, there are regions where PIO is unlikely on the basis of the attitude Bandwidth characteristics alone. In some instances high pitch rate overshoot is a contributor, and limits are placed on the frequency-domain-based metric, ΔG(q) (Figure 10). In others inadequate flight path control is the culprit, so limits are placed on flight path Bandwidth frequency, ω_{BW_γ}. Requirements on pitch attitude Bandwidth versus Phase Delay are presented in Figure 11 (feel system included in the aircraft model) and in Figure 12 (feel system excluded).*

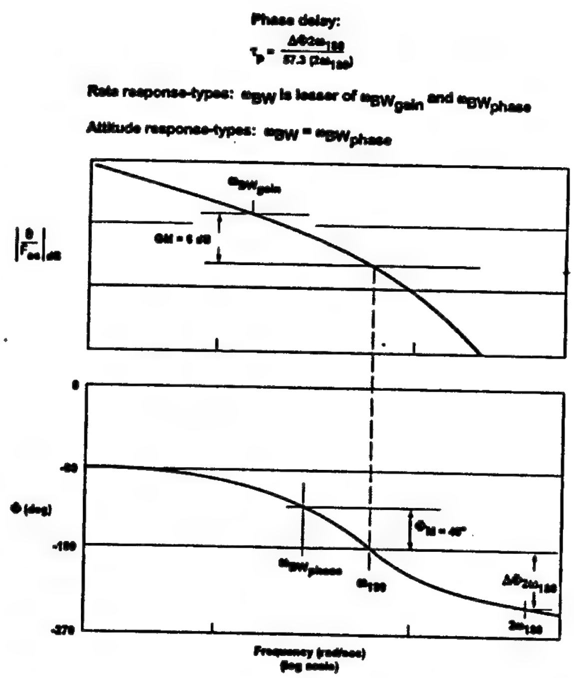

Figure 9. Definitions of pitch attitude Bandwidth and Phase Delay (flight path Bandwidth ω_{BW_γ} is measured from γ/F_{es} and is defined as $\omega_{BW_{phase}}$)

* The lines dividing PIO boundaries on the figures are intentionally very wide. There is no clear division between "no-PIO" and "PIO" and we want to emphasize this fact.

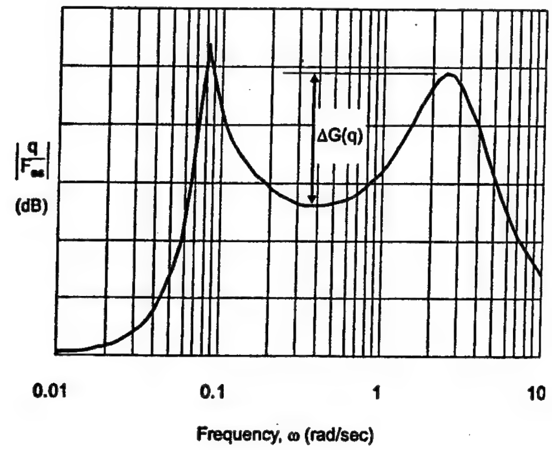

Figure 10. Definition of pitch rate overshoot parameter, ΔG(q)

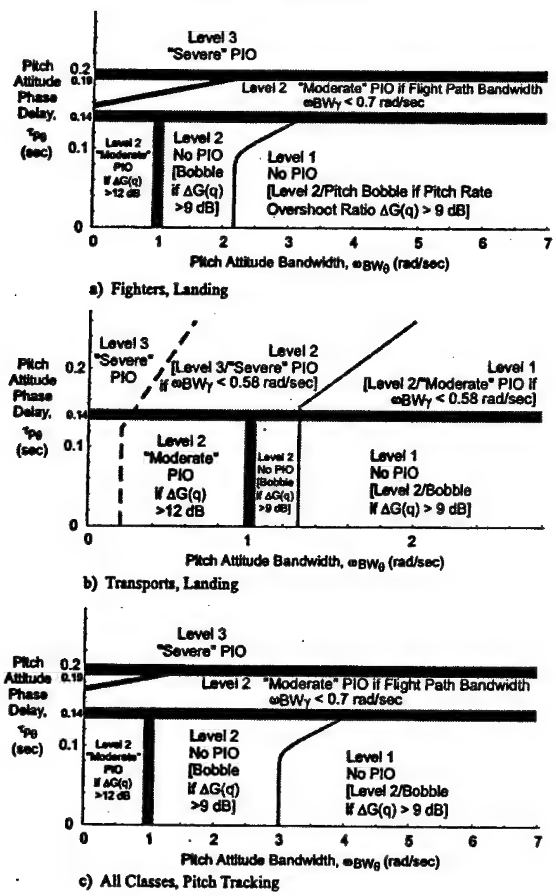

Figure 11. PIO criteria for pitch response (dynamics of the cockpit control feel system included)

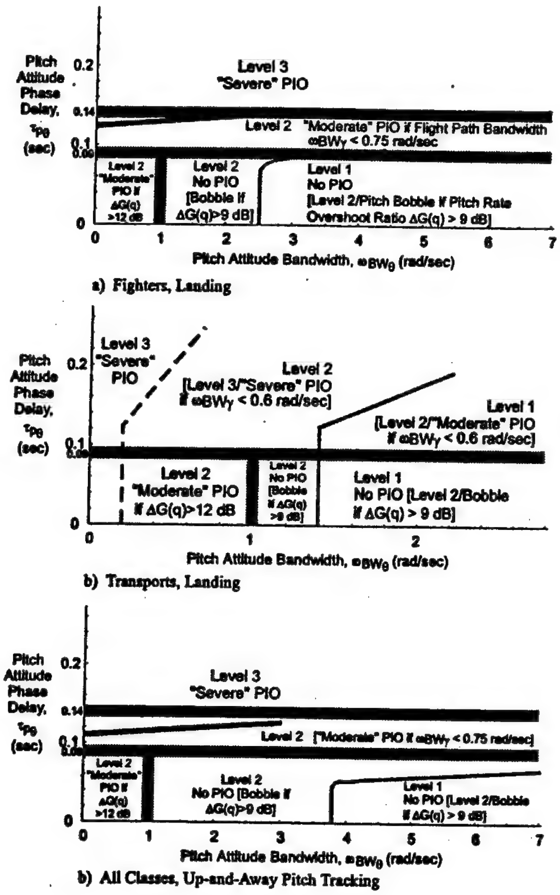

Figure 12. PIO criteria for pitch response (dynamics of the cockpit control feel system excluded)

Roll requirements are given in Figure 13. They are not as comprehensive as those in pitch, in part because of a lack of data and in part because of a lack of concern about severe lateral PIOs. No requirements could be established for other axes at this time.

4. Continue to Apply Criteria as the Accuracy of the Model Improves. – There will be a natural increase in sophistication for the aerodynamics and control system models; there should be a system in place for immediate application of the PIO prevention criteria every time a certain milestone is met.

5. Use High-Gain Maneuvers to Evaluate PIO Tendency in Piloted Simulations. – If ground-based simulation is used to evaluate the new vehicle's characteristics, a minimum set of pilot-in-the-loop, high-gain maneuvers must be evaluated. At this stage, any warnings of PIO tendency by any pilot should be investigated.

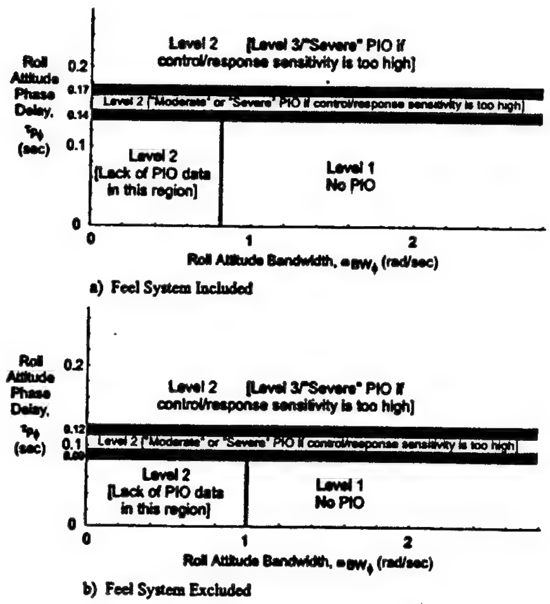

Figure 13. PIO criteria for roll response, all flight conditions, all aircraft categories

A minimum of five qualified evaluation pilots should be used, if at all possible. The pilots *must* be aware of the concern for PIO and familiar with the maneuvers to be flown. Typically such pilots are trained experimental test pilots from one of the military pilot schools. Test pilots have been provided the opportunity to fly a wide variety of aircraft and should be more capable of relating their exposure to the test airplane to previous experiences in similar aircraft.

There is always an initial reluctance to fly certain maneuvers because they are not "operationally relevant," or because "no experienced, trained pilot would *ever* do *that* in the air." It must be stressed that PIOs are also not operationally relevant, and unusually high-gain or large-amplitude tasks are used in simulations because it is simply not possible to replicate every possible scenario for PIO. Tasks should include, but not be limited to, attitude captures, precision landings, aerial refueling (or close formation flight), and command tracking. Pilots should always be aware of the potential for PIO when any task is flown, even if it is not intended to look specifically for PIO. Engineers and pilots must work together in simulations, because it is possible that PIOs can go undetected by the pilot.

In general, based on recent experience with PIOs in piloted simulation, the following observations can be made. For an airplane evaluated by several qualified experimental test pilots in a particular flight condition/configuration/loading combination, using a well-defined high-gain PIO assessment task:

- If the simulated airplane is judged by all of the pilots to have Level 1 or near Level 1 handling qualities (Cooper-Harper Handling Qualities Ratings (HQRs) of 4 or better), and is judged to have no PIO tendencies, PIO is not likely in the real airplane.
- If the simulated airplane is judged by one or more of the pilots to be Level 3 or worse (HQR 7 or worse), and to have tendencies toward PIO, severe PIO is highly likely in the real airplane.
- If the simulated airplane is judged by most or all of the pilots to be in between in HQR (4, 5, or 6), and to possibly exhibit some tendency to PIO, the simulation cannot be considered conclusive. In this case, engineering expertise and quantitative analysis using PIO-detection methods must be applied to the simulation data. Absence of evidence of PIO will indicate a reasonably safe airplane for flight testing.

It must be emphasized that the extrapolation from simulation to flight will be only as good as the simulation model. Significant errors in the model, or significant nonlinearities in the airplane not incorporated into the model, can eliminate any value to the simulation results.

6. Apply PIO Detection and Prevention Devices During Developmental Flight Testing. – As with simulation, flight testing must include maneuvers intended specifically to look for PIO. In addition, reliable real-time PIO detection devices – either onboard or operated remotely via telemetry – will help monitor the occurrence of PIOs. Such devices may include active intervention to prevent or recover from PIOs.

7. Extend Test Inputs and Application of Criteria to Large Input Amplitudes. – The fundamental theory behind Bandwidth is that it is a measure of piloted closed-loop activity, and hence is most effective for describing small-amplitude control inputs. There is a natural reduction in Bandwidth for any physical system as input amplitude increases beyond a certain value, resulting from limitations of the airplane, limiting on actuator rates and positions, etc. Still, experience has shown that the Bandwidth criteria defined above are very effective at predicting PIO susceptibility for quite large inputs.[71] If any of the PIO-susceptible regions is reached for a reasonable input size, PIO is likely. Frequency sweeping should emphasize input amplitudes that result in aircraft responses at and above the Bandwidth frequency that approach the operational limits for the aircraft. The data obtained in such sweeps will both enhance the fidelity of simulation models and help prevent large-amplitude PIOs.

8. Update Ground Simulation Models With Flight Data. – This is a step that is always desired in a

developmental program, but experience has shown that it is not always done, or at least not in a timely manner. It should be possible to continue to make use of ground simulation to search for PIO, but the simulator is only as good as the model. A regular process must be implemented to keep the simulation model as up-to-date as possible, and regular sessions should be scheduled to look for PIO tendencies with the updated model.

9. Include PIO Recognition as a Part of the Training Syllabus for Pilots. – Whether the aircraft is commercial or military, there is always a potential for the occurrence of PIO in follow-on flight testing or operational use. This may be as a result of a design flaw, an excursion into untested flight conditions or loadings, or following a failure. It is not likely that the typical fleet pilot will encounter PIO very often, and perhaps never. Pilots who are aware of the characteristics of PIO, however, are much more prepared for dealing with the event, and for accurately reporting it to cognizant agencies.

10. Be Prepared for PIO. – See step 1. If there is one overwhelming recommendation that can be made, it is that all parties involved in the development of a new aircraft must always be prepared for the occurrence of PIO. It should not come as a complete surprise.

Structural Interactions

The effects of flexibility on the flight dynamics of aircraft have been shown to be quite significant, especially as the frequencies of the elastic modes become lower and approach those of the rigid body modes. The handling characteristics of such vehicles are altered significantly from those of a rigid vehicle,[72] and the design of the flight-control system may become drastically more complex.[73,74]

Shown in Table 3, for example, are the lowest frequencies of the structural vibration modes for several flight vehicles. This data shows that these frequencies can be lower than 3 Hertz, and in some advanced supersonic-transport configurations (denoted SCR in the table) the frequencies are as low as one Hertz. Some are well within the bandwidth of the pilot and primary flight-control system, and others may certainly be excited by turbulence.

In this paper studies from two simulations will be presented, involving two similar aircraft. The simulations were performed in NASA Langley's simulation facility. The results from these studies demonstrate a phenomenon known as biodynamic coupling and feedthru, which lead to significantly degraded handling characteristics. And it will be demonstrated that this phenomenon is directly related to the vehicle's elastic effects. That is, if the vehicle were more rigid, the phenomenon would not be present.

Table 3. Examples of lowest structural vibration frequencies

Trends in Elastic Frequencies

Aircraft	Frequency (r/s)
B-1	13
Concorde	13+
C-5A	11.
NASP	~18.
SCR designs	~6.5

Case Study 1

Consider a generic, large, swept-wing, high-speed aircraft with a conventional empennage, with descriptive data given in Table 4. The analysis herein will focus on the longitudinal dynamics, although the simulation study addressed both axes. The pitch-rate-to-elevator frequency responses (rad/sec/deg) for the elastic- and (two similar) rigid-vehicle models are shown in Figure 14. The short-period modal frequency near 2 rad/sec, and the first aeroelastic modal frequency near 2 Hz, are evident.

The simulation study in this case used a precision-tracking task, with artificially-generated commands displayed on a heads-up display. This task was flown multiple times by several test pilots in NASA Langley's Visual-Motion Simulator.[75] One of the important experimental variables was the in-vacuo vibration frequency of the first symmetric fuselage mode (ω_1), a parameter in the dynamic model. Of interest was the effect of this modal frequency on the handling characteristics, with everything else (task and all other parameters in the dynamic model) held constant.

The results from this experiment are presented in Figure 15, in which the degradation in handling qualities as only the first elastic modal frequency is reduced is clearly evident. The handling qualities of the vehicle if it was purely rigid (all elastic deformations held at zero in the simulation) were rated Level 1, while the handling characteristics of the baseline vehicle (with lowest frequency of 2 Hz) were given an average Cooper-Harper HQR of about 4.5, or Level 2. Finally, the handling characteristics degraded to Level 3, or an average Cooper-Harper HQR of around 7, when the lowest elastic mode frequency was reduced to 1.4 Hz.

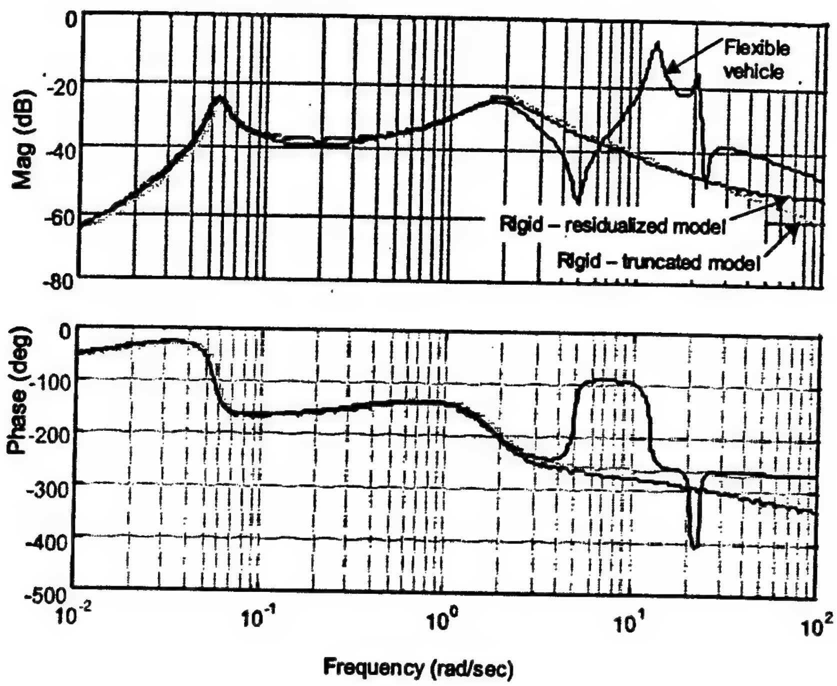

Figure 14. Pitch rate to elevator frequency responses - flexible and rigid models

Table 4. Geometry, mass, and inertia of vehicle – Case Study 1

Vehicle Geometry	$\bar{c}$ = 15.3 ft, mean wing chord
	b = 70.0 ft, wing span
	S_{ref} = 1946 ft^2 wing planform area
	Λ = 65 degree wing sweep angle
Weight	W = 288,017 lb
Inertias	I_{xx} = 950,000 slug-ft^2
	I_{yy} = 6,400,000 slug-ft^2
	I_{zz} = 7,100,000 slug-ft^2
	I_{xz} = - 52,700 slug-ft^2
	$I_{xy} = I_{yz} = 0$
Modal generalized masses	M_1= 183.6 slug-ft^2
	M_2 = 9586.5 slug-ft^2
	M_3 = 1334.4 slug-ft^2
	M_4 = 43,596.9 slug-ft^2
Modal vibration frequencies	ω_1 = 12.6 rad/sec
	ω_2 = 14.1 rad/sec
	ω_3 = 21.2 rad/sec
	ω_4 = 22.1 rad/sec
Modal dampings	$\zeta_i = 0.02, i = 1, 2, 3, 4$

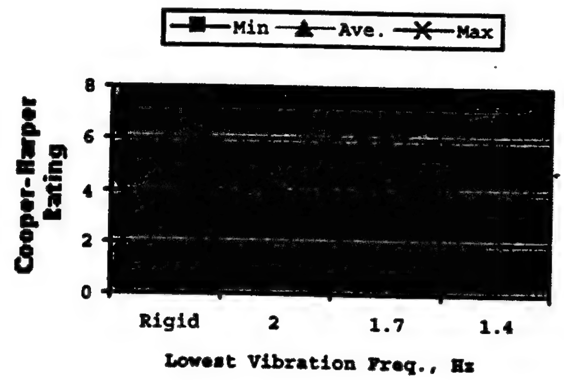

Figure 15. Effect of increased flexibility on Handling Qualities Rating

Case Study 2

Drawing from the above earlier study, a second dynamic-aeroelastic simulation was performed in NASA Langley Research Center's Visual-Motion Simulator.[75] The vehicle in this case was an even larger high-speed aircraft than that in Case One, with weight at the study flight condition around 300,000 lb, and a length of over 250 ft. The wing was a double delta, and the lowest vibration frequencies were around one Hertz. The three lowest-frequency modes in each axis were modeled, for a total of six elastic modes.

Six test pilots were asked to compare maneuvers performed with and without aeroelastic dynamic effects (ASE) present in the real-time simulation model. The pilots' Cooper Harper HQRs for a lateral-offset landing maneuver are shown in Table 5. The offset landing task is a challenging maneuver that requires the pilot to aggressively correct for a 300-ft lateral offset from the runway centerline at an altitude of 250 ft. Results indicate that the presence of dynamic aeroelastic effects in the simulation model greatly degraded the aircraft handling qualities, particularly in the lateral axis in this task. In some cases lateral/directional HQRs degraded from Level 1 to Level 3 as a result of the aeroelastic effects.

Table 5. Impact of Aeroelastic Effects on Handling Qualities Rating – Case Study 2

	Longitudinal HQRs						Lateral/Directional HQRs					
Pilot	A	B	C	D	E	F	A	B	C	D	E	F
ASE OFF	3	4	4	5	4	5	3	3	3	4	4	5
ASE ON	6	7	6	7	5	6	4	7	8	6	5	7

Pilot comments indicated that cockpit vibrations due to aeroelasticity degraded the ratings for at least two subtly different reasons. The first is that the vibration environment simply had a negative impact on the comfort level or ride quality at the pilot station. Pilots therefore increased their ratings because the extreme vibrations tended to increase their perception of workload.

Pilots also remarked that cockpit vibrations tended to influence the precision of their control inputs. Some pilots indicated that the vibrations actually resulted in involuntary control inputs. This aeroelastic effect is referred to as *Biodynamic Feedthru.*[76] In some cases, the combination of the aeroelastic aircraft, the control stick, and the pilot's biomechanical dynamics may result in a closed-loop system that is unstable or lightly damped. In such instances, cockpit vibrations may cause resonance of the pilot's biodynamic frame, resulting in sustained feedthru of aeroelastic vibrations back into the control stick, a condition that is referred to as *Biodynamic Coupling.* An analytical model of a similar coupling phenomenon was presented by Smith and Montgomery,[77] based on the analysis of flight data.

Figure 16 presents an analysis of a lateral-offset landing task in which the pilot experienced biodynamic coupling while flying the aeroelastic configuration. Frequency and time data shown in Figure 16 have been normalized as follows: fo = Normalization Frequency, corresponding to peak in voluntary pilot input frequency spectrum obtained from PSD of pilot stick time histories; and To = Normalization Time Step, 1/fo.

The time history at the top of the figure shows lateral cockpit accelerations in g's (dashed line) and lateral stick deflections (solid). Although the units on the two quantities differ, the scaling of ± 1 is convenient since it represents the maximum normalized throw for lateral stick deflection and since lateral g's commanded by the simulation remained in the range of $\pm$ 1 g. The plot in the lower left of Figure 16 shows the power spectral density of lateral accelerations and lateral stick deflections applied to a segment of the time history. The frequency spectrum of the pilot's control inputs during this period lies within the pilot's voluntary input bandwidth. The frequency spectrum of the lateral accelerations at the pilot station shows some content at the first and second antisymmetric mode frequencies due to minor turbulence excitation of these structural modes.

The power spectrum of a later segment of the time history is shown in the lower middle of Figure 16. This plot indicates the bulk of the pilot's input spectrum remains in his voluntary frequency band, but it also shows some frequency content of the pilot's inputs in the range of the lateral elastic modes. Once the pilot begins to move the stick at the resonant frequency of the first antisymmetric structural mode there is tremendous potential for the lateral mode to be excited by the control inputs, producing larger lateral accelerations at the pilot station. These lateral accelerations move the pilot's frame in a fashion that produces involuntary control inputs that further excite the structural mode. The third power spectrum plot at the lower right of Figure 16 covers the final segment of the time history. Here, the spectrum of the pilot's stick input exhibits a pronounced resonant peak at the frequency of the first antisymmetric structural mode. It is highly unlikely that the pilot's inputs in this frequency range are voluntary. Video of the seated pilot clearly depicted a correlation between lateral stick inputs and involuntary lateral motions of the pilot's upper body. A clear change in the character of the pilot's stick inputs is apparent in the time history, indicating well-developed biodynamic coupling as lateral accelerations feed through the pilot's frame and back into the control inceptor. The pilot could break the involuntary coupling loop if he released the stick, but he is approaching the flare and therefore is unwilling to do so.

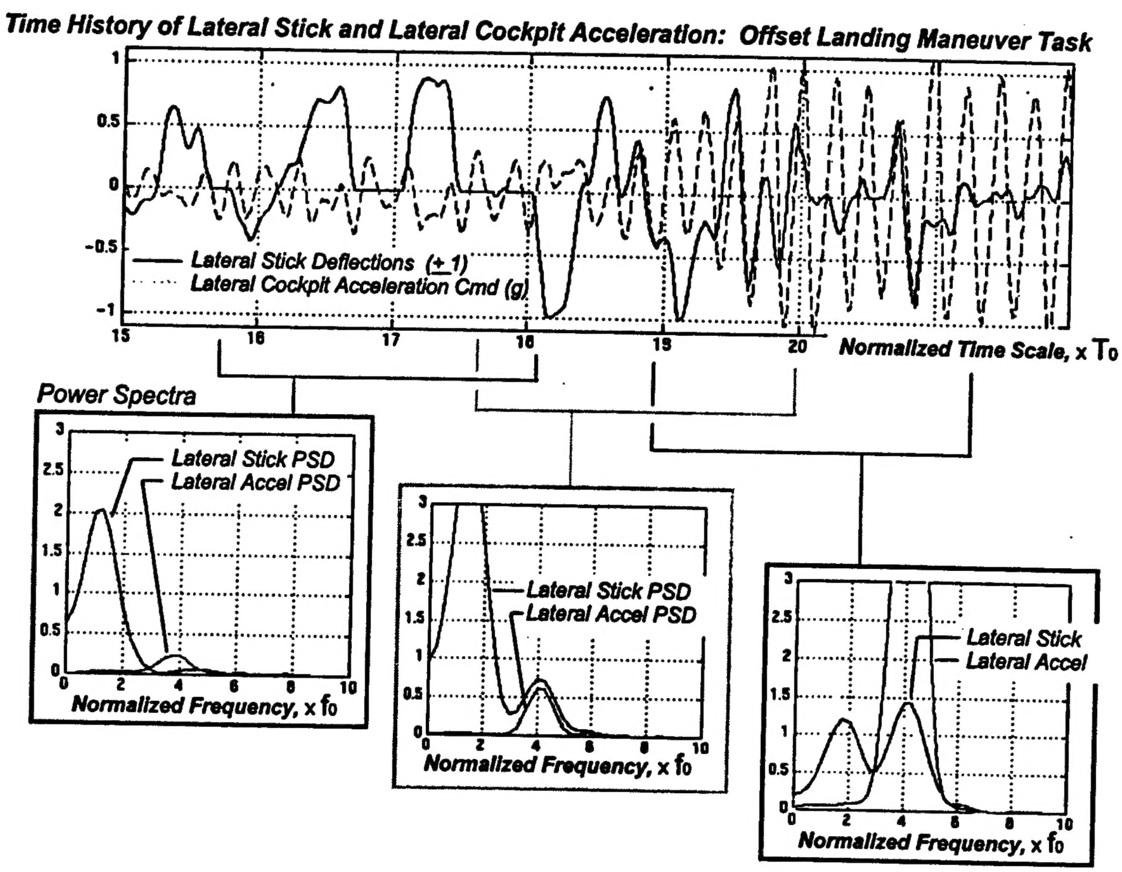

Figure 16. Example of biodynamic coupling incident

To summarize, biodynamic coupling is indicated when cockpit vibrations due to elastic modes feed directly through the pilot's arm and back into the control stick, creating a lightly damped or unstable closed-loop system. The phenomenon is evidenced by a resonant peak in the power spectrum of the pilot's stick inputs at the frequency of one or more of the dynamic elastic modes. The tendency to couple with structural modes appears to increase when pilots tighten their grip on the stick, often in preparation for the flare as the aircraft nears the runway. The phenomenon is influenced by design of the control inceptor and control laws, piloting style and probably even various aspects of the pilot's physical stature. These results highlight the importance of modeling and simulation of aeroelastic effects when assessing the flight dynamics and flying qualities of large flexible aircraft.

Conclusions

The evolutionary and revolutionary changes to handling qualities that have occurred in the past ten-years have not lessened their importance. Despite the increasing focus on unpiloted aircraft, there will be, for the foreseeable future at least, a requirement to design and verify the existence of desirable handling qualities in piloted aircraft.

The familiar handling qualities document for fixed-wing airplanes, MIL-STD-1797A, has been relegated to handbook status, but it remains an excellent design guide. The V/STOL document, MIL-F-83300, has not been updated since its release over thirty years ago and is sorely out of date. Still, it too should be considered a reference source for V/STOL aircraft. The tri-service rotorcraft specification, MIL-H-8501A, is retired and, for the Army at least, replaced by the Aeronautical Design Standard ADS-33E-PRF. The latter serves as the most modern, thorough handling qualities specification.

Though the documents are retired, their goals should not be ignored: to provide satisfactory handling qualities for any type of air vehicle. Proper application of criteria requires an understanding of the field of handling qualities, and it is a mistake to assume that the field has outpaced our knowledge base and the associated criteria.

There remain formidable challenges. Application of the *intent* of the specifications – to assure satisfactory

handling qualities – without rigidly following the *details* of the requirements – calls for greater understanding of those requirements. The expert must be well-versed in pilot modeling and the interactions between pilot and aircraft. Effects of multi-axis control must be quantified. Work needs to be done to provide more updated guidance to designers of fixed-wing V/STOL aircraft. The impact of flexible modes on handling qualities, especially as transport aircraft continue to grow in size, must be thoroughly understood and quantified. Pilot-induced oscillations continue to occur, and likely will always occur, so methods for their prediction and suppression must be refined.

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